Jurnal Kejuruteraan 31(1) 2019: 149-153
https://doi.org/10.17576/jkukm-2019-31(1)-18

Reactivity Controlled Compression Ignition Engine: A Review

(Enjin Pencucuhan Mampatan Kereaktifan Terkawal: Ulasan)

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Received 24 April 2018, Received in revised form 11 January 2019
Accepted 8 February 2019, Available online 30 April 2019

ABSTRACT

Reactivity Controlled Compression Ignition (RCCI) is an efficient dual-fuel engine combustion technology that can offer low emission level in internal combustion engine technology. RCCI technology works by generating reactivity stratification in the cylinder with two fuels of different cetane numbers. To accomplish reactivity stratification, the fuel with lower reactivity is premixed with air before charging into the combustion chamber. The fuel with higher reactivity is injected subsequently using a direct injector. By properly manipulating the fuel ratio and the injection timing, one is able to regulate the combustion phasing and lessen the rates of pressure rise and heat release thanks to the reactivity gradient. Meanwhile, factors such as compression ratio (CR) and piston bowl geometry could influence the characteristics of RCCI. Evaporation, mixing, and combustion processes are dependent on the fuel type. In this paper, recent progress to improve the combustion processes with several aspects of changing of RCCI engine parameter are reviewed, such as management strategy, compression ratio, EGR rate, and bowl geometry.

Keywords: High Reactivity Fuel; Low Reactivity Fuel; Engine Management; Cetane Number; Injection Strategy

ABSTRAK

Enjin Pencucuhan Mampatan Kereaktifan Terkawal (RCCI) adalah teknologi pembakaran dwi bahan api yang cekap dan boleh membantu dalam membangunkan teknologi enjin pembakaran dalaman dengan tahap emisi karbon yang rendah. Teknologi RCCI berfungsi dengan menghasilkan stratifikasi kereaktifan dalam silinder dengan dua bahan api yang mempunyai nombor setana yang berbeza. Dalam mencapai stratifikasi kereaktifan, bahan api dengan kereaktifan yang lebih rendah dicampurkan dengan udara sebelum dimasukkan ke dalam kebuk pembakaran. Bahan api dengan kereaktifan yang lebih tinggi kemudiannya disuntik menggunakan penyuntik langsung. Dengan memanipulasi nisbah bahan api dan masa suntikan yang betul, pembakaran dapat dikawal selia secara berperingkat dan mengurangkan kadar peningkatan tekanan dan pembebasan haba hasil daripada kecerunan kereaktifan. Sementara itu, faktor-faktor seperti nisbah mampatan (CR) dan geometri mangkuk omboh boleh mempengaruhi ciri-ciri pembakaran RCCI. Proses pencampuran, dan pembakaran adalah sangat bergantung kepada jenis bahan api. Dalam kajian ini, beberapa aspek enjin RCCI dikaji semula, seperti strategi pengurusan, nisbah mampatan, kadar EGR, dan geometri mangkuk.

Kata kunci: Bahan Api Kereaktifan Tinggi; Bahan Api Kereaktifan Rendah; Pengurusan Enjin; Nombor Setana; Strategi Suntikan

INTRODUCTION

The development of modern internal combustion engines are inclined towards reduction of greenhouse gases (e.g. CO_2), augmentation of engine efficiency and prevention of energy shortage. It is known that diesel engine is promising in terms of thermal efficiency; however, problems such as soot and production of Nitrogen Oxides (NO_x) are common in conventional diesel engine as combustion occurs in both rich and lean high-temperature regions. In order to ensure a greener environment, an efficient combustion engine that can offer low emission level is highly desirable.

RCCI engine was invented by Kokjohn et al. (2009) inspired from the concepts of dual-fuel Homogeneous Charge Compression Ignition (HCCI) and premixed charge compression ignition (PCCI) combustions. It works by blending at least two different fuels to control combustion phasing, duration and magnitude (Reitz & Duraisamy 2015). The schematic diagram of RCCI combustion is shown in Figure 1. The Low Reactivity Fuel (LRF) such as gasoline is injected via the Port Fuel Injector (PFI) which is located inside the intake manifold before it is premixed with air. Meanwhile, the High Reactivity Fuel (HRF) diesel is injected into the cylinder via the Diesel Injector (DI) during the compression stroke. The injection of HRF is accomplished via the single, double or triple injection strategy. Combustion phasing and combustion duration are controlled by the fuel ratio and the spatial stratification between the fuels, respectively.

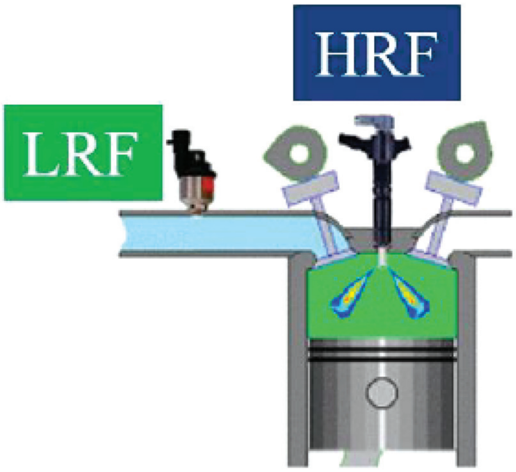

FIGURE 1. Schematic of RCCI engine (Reitz & Duraisamy 2015)

As proven experimentally by Kokjohn et al. (2010), RCCI is able to meet the emission regulations without depending on NOx and soot after-treatment. Its efficiency is high at a wide range of engine loads, i.e. its peak gross indicated efficiency is 56% at IMEP operating point of 9.3 bar. As compared to the conventional diesel combustion engine (without EGR), the NOx of RCCI is significantly smaller (about three orders of magnitude). Meanwhile, the soot level and the gross indicated efficiency of RCCI are six times smaller and 16.4 % higher than those of conventional diesel engine, respectively. Apart from experimental method, numerical modeling method such as Computational Fluid Dynamics (CFD) has been used to study RCCI and high-EGR diesel combustions. It was reported by the authors that at similar operating condition (i.e. inlet oxygen concentration), RCCI was better in terms of performance: NOx was decreased by two orders of magnitude; gross indicated efficiency was enhanced by 11.5 % and soot was decreased by a factor of ten. C. Kavuri et al. (2016) studied the RCCI and the gasoline compression ignition (GCI) combustion engines at high load (20 bar IMEP) and low speed (1300 rev/min) conditions. The combustion characteristics in both engines were similar, with a near TDC injection initiating and controlling the combustion phasing for both the strategies. However, RCCI could offer more control on combustion phasing thanks to the shorter ignition delay of diesel fuel (as compared to gasoline).

ENGINE MANAGEMENT IN RCCI ENGINES

The fuel efficiency of diesel engine is high. Hence, it is commonly used for transportation and power generation. Nevertheless, the NOx and soot emissions from the diesel engines are high, thus causing environmental pollution. Hence, the associated engine management in terms of injection related parameters, fuel ratio, EGR rate, bowl geometry and CR should be performed prudently.

FUEL RATIO

Fuel ratio (i.e. mass, energy or volume ratio, taken as low reactivity fuel : high reactivity fuel) affects the in-cylinder reactivity (Li et al. 2015). In RCCI, the commonly used Low Reactivity Fuels (LRFs) are gasoline, natural gas (NG), methanol, and ethanol. Meanwhile, diesel is usually served as HRF (high reactivity fuel). The common fuels in diesel engine are gasoline and diesel. Gasoline is well known for its high volatility; therefore, its evaporation rate is high and a premixed charge can be attained using PFI. Property such as resistance to auto-ignition of gasoline (which is low in cetane number) can be enhanced in order to prolong its pre-combustion mixing time. However, combustion is hardly achievable using gasoline due to its poor auto-ignition quality. In general, the fuel reactivity denoted as CN can be calculated from Eq. (1) as:

$$CN_{dual-fuel} = \frac{CN_{low}X_{low} + CN_{high}X_{high}}{X_{low} + X_{high}} \qquad (1)$$

Here, CN is the cetane number and χ is the mole fraction. The subscripts "high" and "low" denote high and low reactivity fuels, respectively. The fuel ratio can affect both reactivity and ignition delay. Usually, ignition delay time increases with respect to the ratio of LRF. Note, ignition delay is a function of engine specification and operating condition. Li et al. (2015) investigated the effect of fuel ratio on the gasoline/biodiesel fueled RCCI engine. They reported that increased gasoline could reduce NOx and soot emissions thanks to the more homogeneous combustion. Li et al. (2017) studied the effect of LRF ratio on engine performance and emission. As reported, the LRF ratio is as high as 90%. Numerous reports have revealed that the blending of LRF could enhance the ignition delay by limiting the CA50.

Since the ignition delay–temperature curve of each fuel is unique, the operating range of each fuel (where peak efficiency is achieved) is quite narrow (see Figure 2). For instance, if the representative temperature of 750K is opted and the required ignition delay for achieving optimum combustion phasing is ~40° CA, the use of neat diesel fuel could lead to peak efficiency by providing the optimum fuel reactivity.

INJECTION STRATEGIES

The ignition (i.e. injection process of HRF) strategy could affect the performance of RCCI engine. These injection strategies include single, double and triple pulses. In fact, the portion of HRF injected may be different in each pulse. The SOI timing associated to each pulse can be optimized as well. The laboratory setup of a typical HD-type diesel engine is schematically shown in Figure 3.

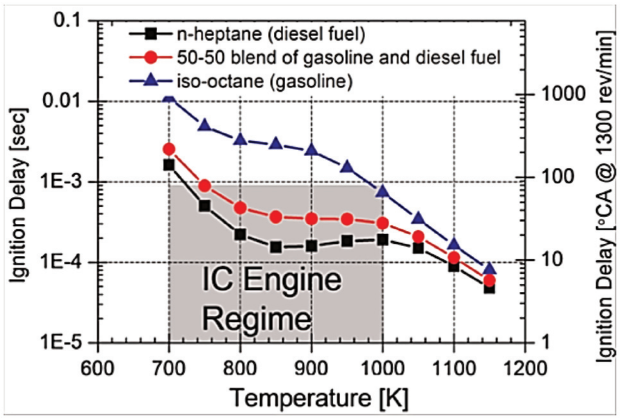

FIGURE 2.Comparison of constant-volume ignition delays calculated using the SENKIN and the reduced PRF mechanism. S.L. Kokjohn et al. (2010)

RCCI combustion is performed via blending two fuels of different auto-ignition characteristics. During the first injection (see Figure 4), the squish conditioning pulse is delivered into the squish region in the vicinity of the -60 ATDC. The main aim is to regulate the local fuel reactivity for more completion combustion in the outer part of the cylinder. The second pulse is injected near the -35 ATDC targeting the bowl region of the cylinder. The ignition source is thus generated (region of high reactivity).

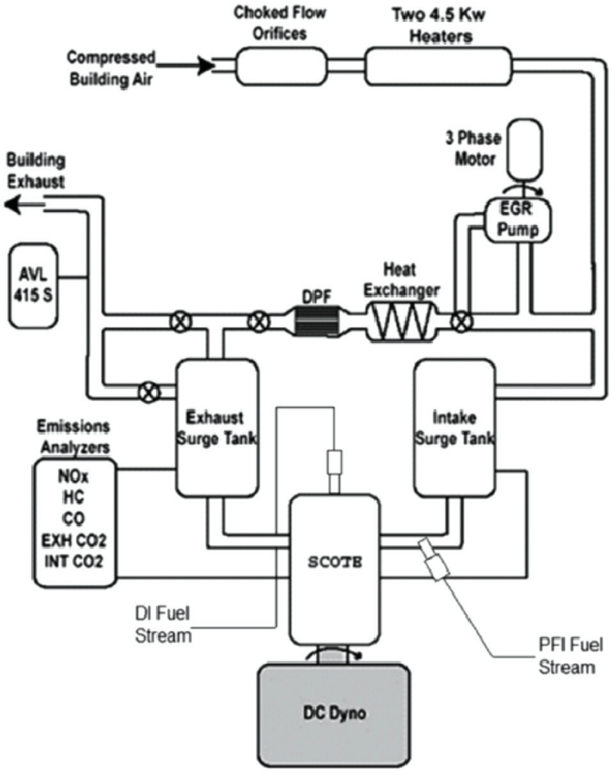

FIGURE 3. Diagram of the engine laboratory setup. The premixed fuel is delivered through the PFI

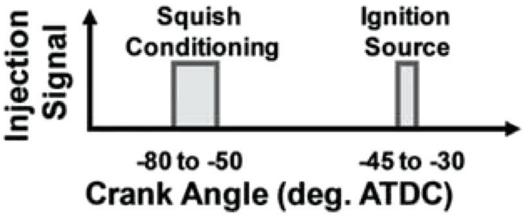

FIGURE 4. Injection strategy used for split injection dual fuel RCCI combustion

Nieman et al. (2012) studied the performances of single and double injections in NG and diesel fuel RCCI engines numerically. The IMEP was set as 23 bar and the optimal SOI timing was prescribed as -81.1° CA ATDC. These operating conditions were obtained via MOGA. As reported, the double injection method gave higher level of soot emission. The changes in NOx, CO and UHC emissions were not apparent nevertheless. In most cases, the effects of single and double injections on the emission levels are still inconsistent (Nieman et al. 2012; Li et al. 2014; Li et al. 2017; Azmi et al. 2018).

EGR RATE

RCCI has been proposed as it could reduce the usage of EGR in CI engines (Inagaki et al. 2006; Kokjohn et al. 2010). However, RCCI should be coupled with EGR at high load condition in order to reduce PRR. At this condition, both NOx emission and combustion noise values are at their minimum levels. The EGR rate can be calculated through the ratio of intake CO_2 to exhaust CO_2 levels. The effect of EGR rate on the engine performance and emission has been studied. It is apparent that PPR, NOx and soot emissions can be reduced by increasing the EGR rate (Wu et al. 2015; Yu et al. 2013). Nevertheless, the low NOx and soot emission levels would lead to low combustion temperature (Akihama et al. 2001; Li et al. 2015).

Li et al. (2015) applied EGR in RCCI engine powered by methanol and diesel for medium load application. As reported, the necessity of using EGR is dependent on the initial temperature. If the initial temperature is lower than the critical number (i.e. 380K), it is not necessary to use EGR and the methanol fraction can be manipulated to retain the engine performance. In addition, cooled EGR could lead to decreased NOx emission at the expense of higher soot and UHC. This claim has been further validated by Yu et al. (2013).

COMPRESSION RATIO

Engine efficiency is dependent on Compression Ratio (CR) as well. In order to increase the range of operating load, Dempsey et al. (2011) developed a RCCI engine with CR as low as 11.7. In addition, Jia and Denbratt (2015) investigated the effect of CR (i.e. 14 and 17) on the performance of NG/diesel fueled RCCI engine. It was found that the EGR temperature at CR 14 was higher as compared to that at CR 17 due to the slower combustion in the former case. In terms of emission level, CR 14 showed reduction in NOx and improvement in UHC. Therefore, CR 14 is more preferable in high loading condition due to the PPRR limitation of the engine.

COMPRESSION RATIO

The piston bowl geometry could affect the air-fuel mixing process (hence combustion) significantly. Li et al. (2016) studied the influence of bowl geometry on the high-speed RCCI engine (powered by biodiesel and gasoline). The bowl geometries studied were HCC (Hemispherical Combustion Chamber), SCC (Shallow depth Combustion Chamber) and OCC (Omega Combustion Chamber) as illustrated in Figure 5. As reported, the original OCC design adopted in the Toyota diesel engine was the best in terms of mixing-controlled combustion. On the other hand, SCC was well suited for RCCI as promising combustion and performances can be attained at lower NO, CO, and soot emission levels.

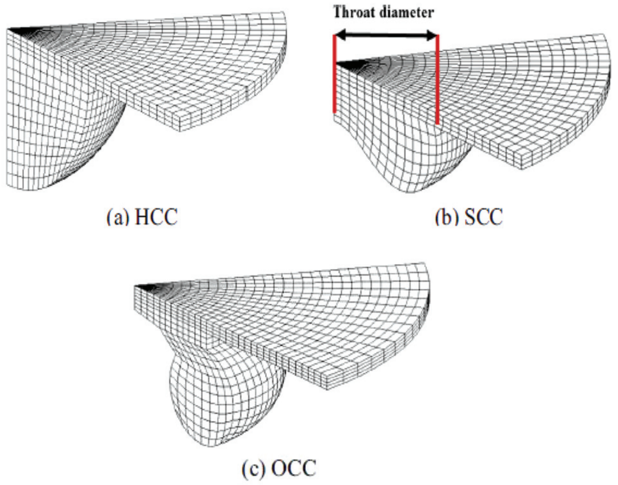

FIGURE 5. Generated grid of bowl geometries Li et al. (2016)

Kokjohn and Reitz (2013) have studied the air-fuel mixing and combustion processes for piston bowl engine. The suitable piston for premixed fuel has been carefully designed as the heat transfer performance during combustion is dependent on the surface area (Li et al. 2014). In fact, heat transfer can be reduced by decreasing the surface to volume ratio (via optimizing the piston shape for premixed fuel) (Splitter et al. 2012); and, the reduction of surface to volume ratio would increase the throat diameter of the bowl, thus further improving the SOI timing of RCCI.

Banajes et al. (2015) tested the performances of three types of bowls (see Figure 6) with single and double injection methods operating at different loading conditions. The stock piston operating at low load condition showed the best mixing performance. Interestingly, all three pistons gave very low soot and NOx emission levels irrespective of the injection strategy. At the medium load condition, both stepped bowl and stock pistons gave similar results. But, at high load condition, stepped piston shows the best performance. Therefore, the stepped piston is the best candidate for RCCI engine.

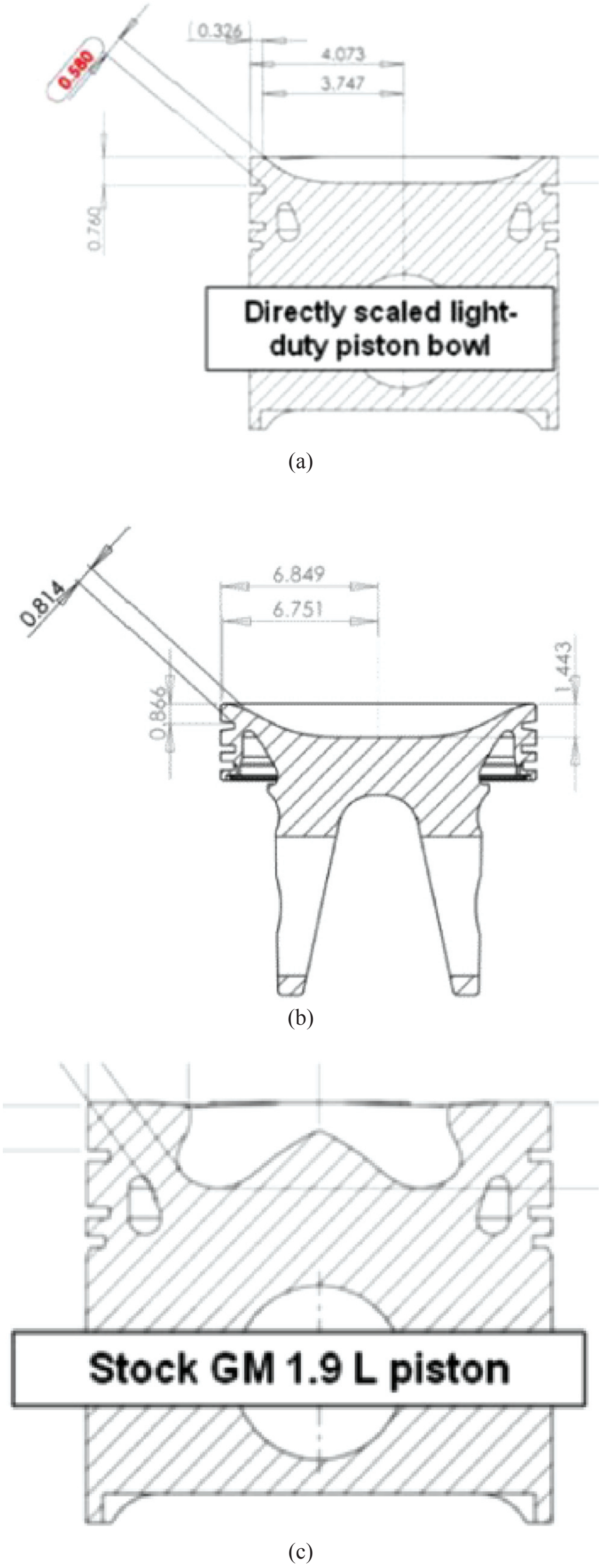

FIGURE 6. Three geometries of piston bowl (a) stepped (b) bathtab (c) stock. Banajes et al. (2015)

CONCLUSION

The progress in RCCI engines management has been reviewed in the current work. As compared to the conventional diesel engine, an optimized RCCI engine is able to give high thermal efficiency, very low soot and NOx emission levels. Many efforts have been developed to enhance the efficiency of RCCI engine, e.g. identifying a RCCI engine that exhibit reasonable reactivity gradient in the combustion chamber. In fact, many parameters can be controlled, such as injection strategy, CR, fuel ratio, EGR rate, and bowl geometry.

It can be concluded that both NOx and soot emission levels can be decreased by increasing the LRF ratio. High EGR ratio could reduce the NOx formation thanks to the reduction of in-cylinder combustion temperature. The piston bowl geometry would affect the heat transfer performance in the RCCI engine as well. And, decreased CR can further extend the engine load. The employment of two injectors inside the RCCI engine can accomodate higher engine load.

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